BOUT:

Boundary Turbulence Simulations Code in Magnetic Fusion Devices

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BOUT Developer Team and Their Quest

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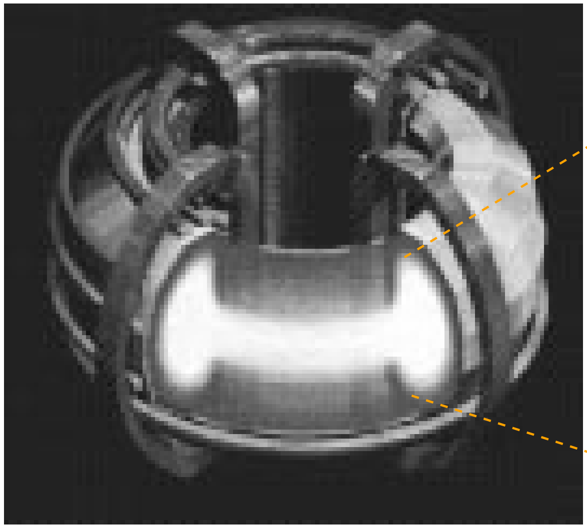
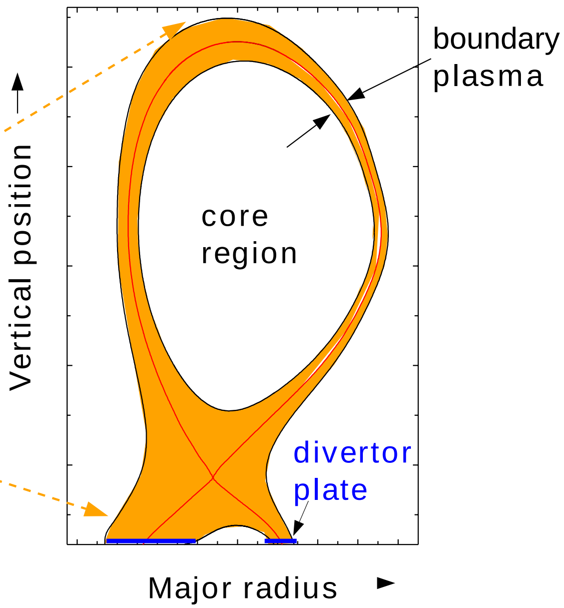
Xueqiao Xu	LLNL	P. Catto/A. Simokov	MIT
D. Ulrich	CSUS		

Tokamak magnetic fusion device

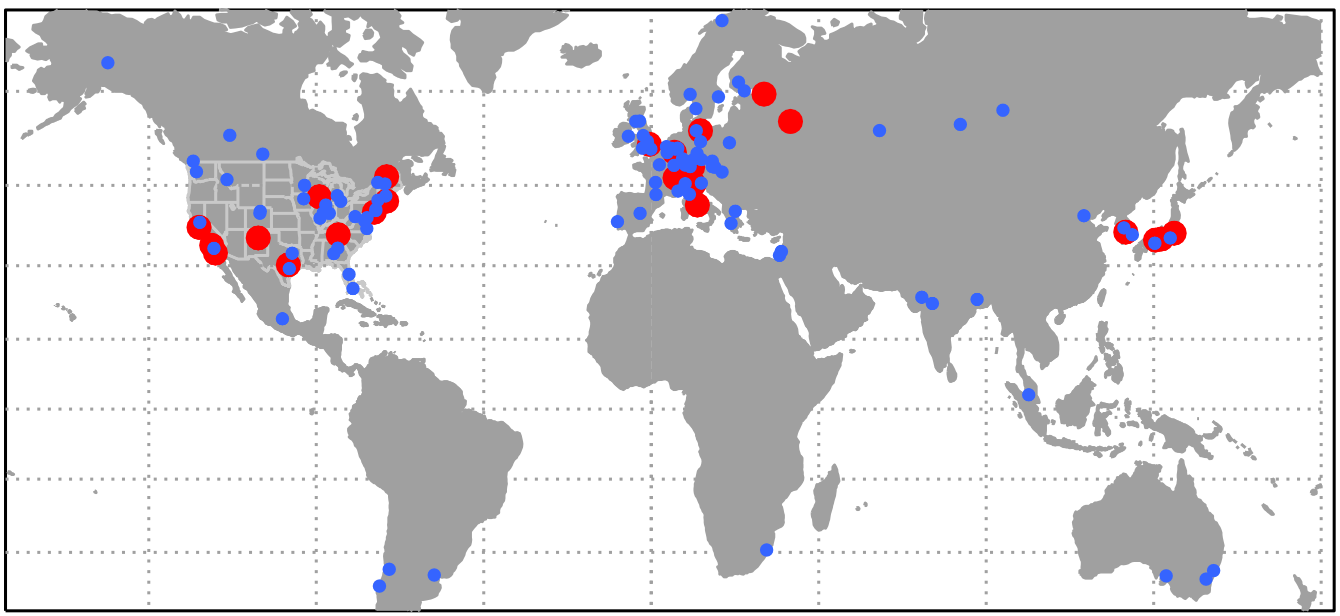


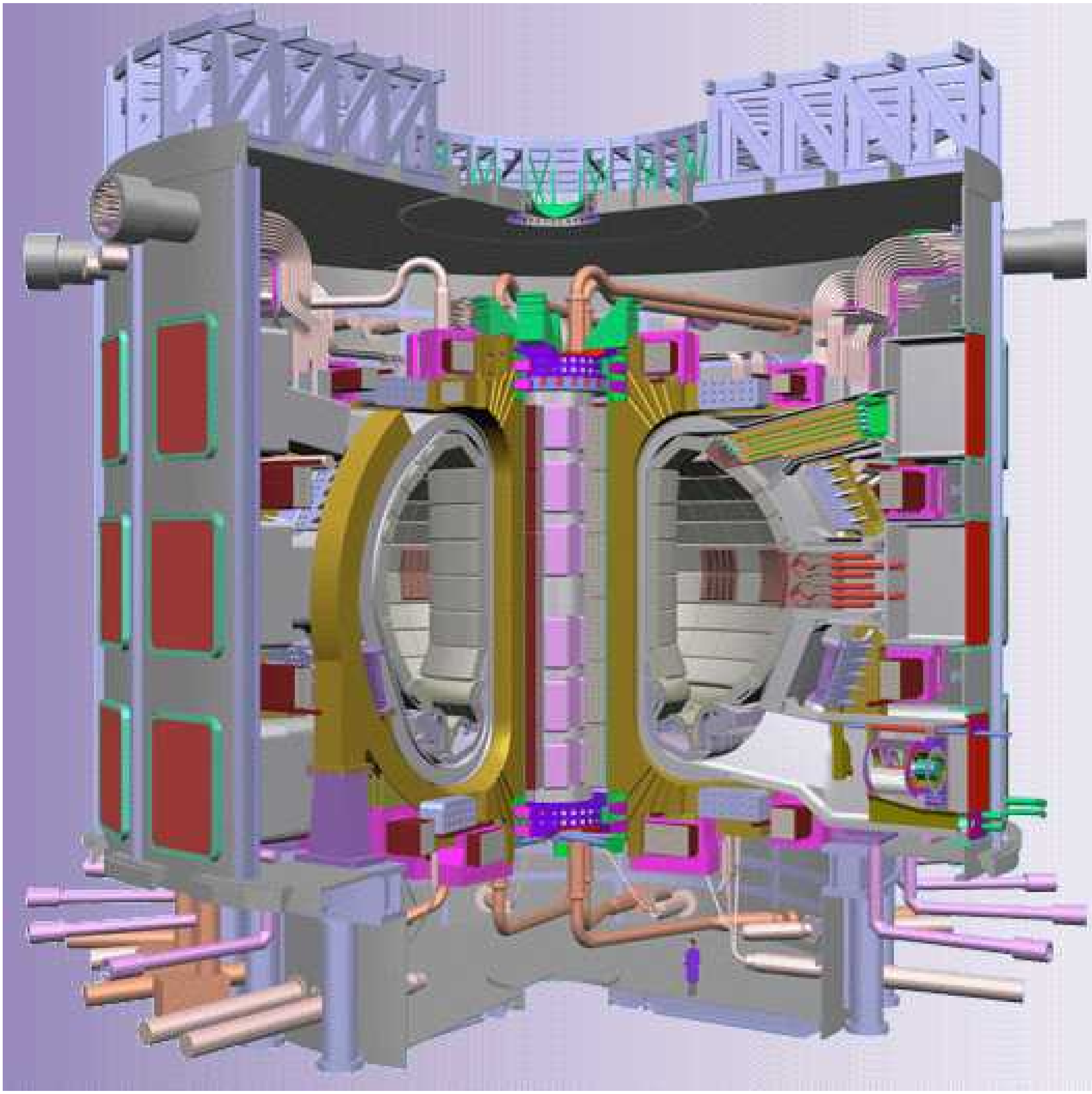
Simulated boundary-plasma region



SCOPE OF THE WORLD FUSION PROGRAM

- At last count - 33 countries, 180 institutions (67 in the US)
- Emphasis Varies
  - US priority to science mission for now, US has withdrawn from burning plasma project - ITER
- EU, Japan give priority to energy mission





FACILITIES AND INFRASTRUCTURE ARE EXTENSIVE

BOUT is 3D EM Boundary Plasma Turbulence Code

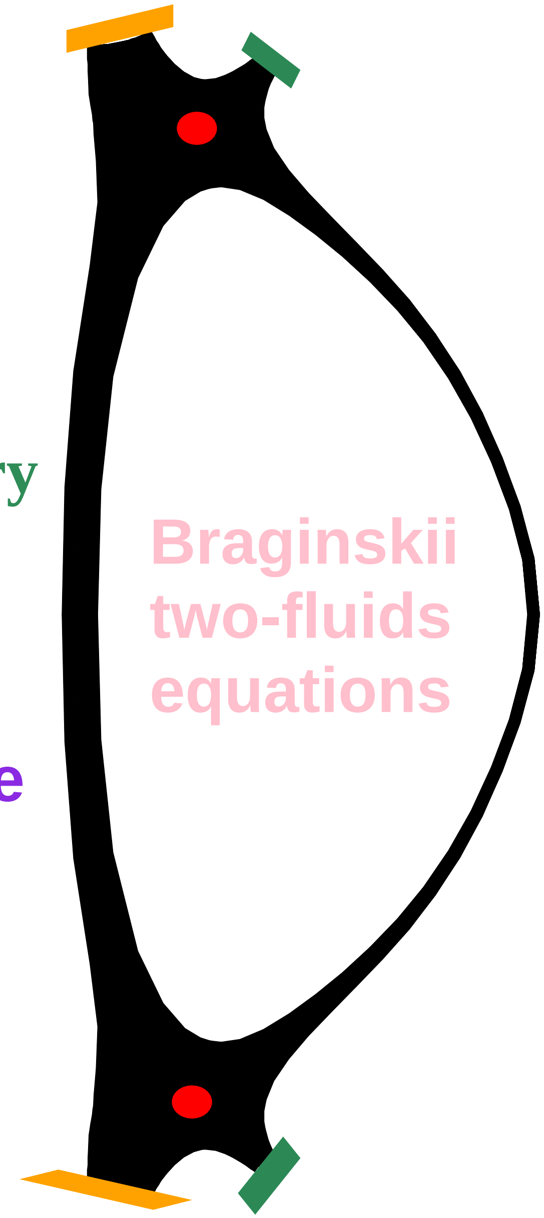
- Boundary Plasma Turbulence has a different characters than in the core and play an important role in core confinement
- BOUT is an unique code to simulate boundary plasma turbulence in a complex geometry

  → Observed large velocity shear layer

  → Proximity of open+closed flux surface

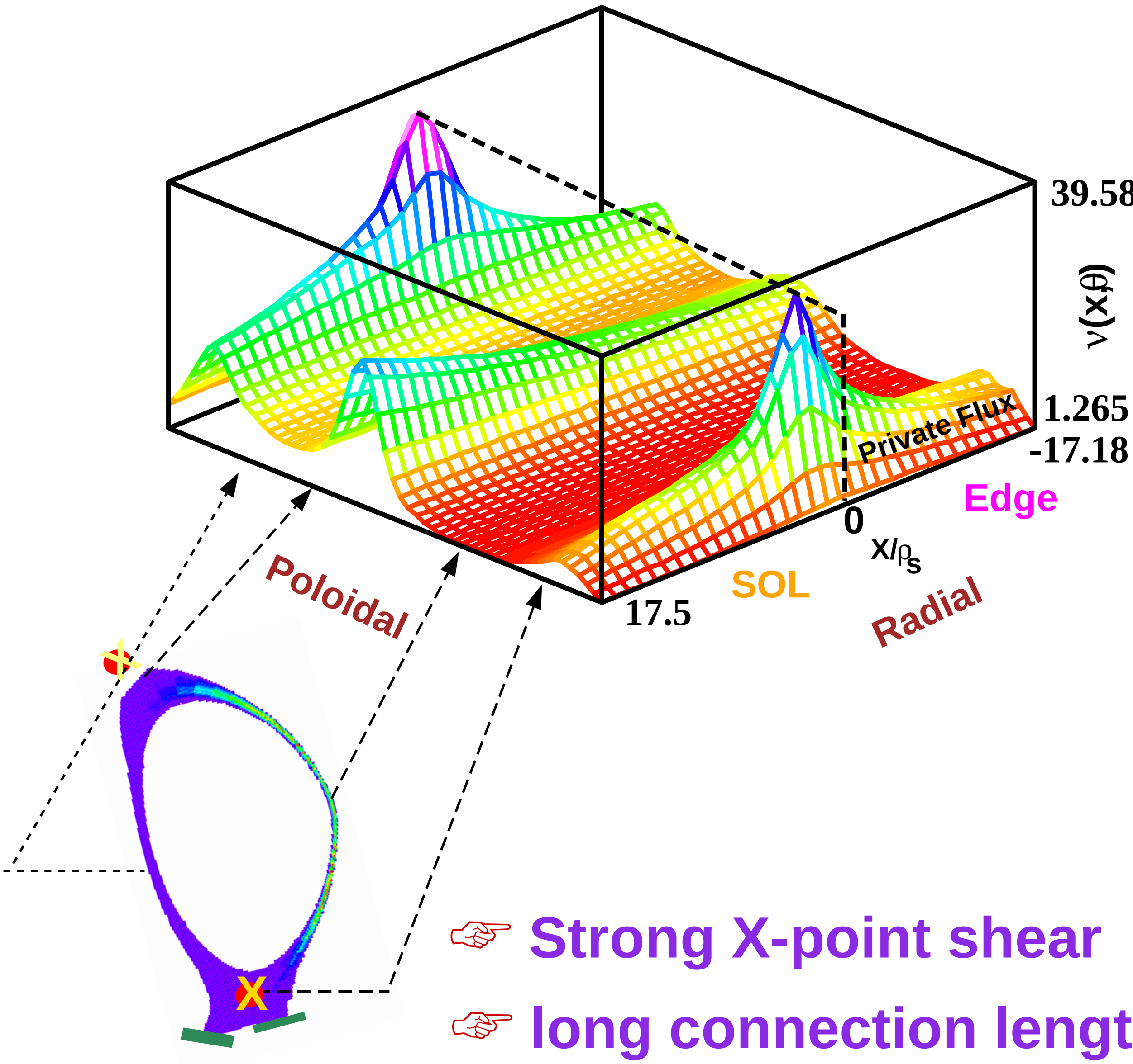
  → Presence of X-point

- BOUT is being applied to DIII-D, C-mod, NSTX, ITER for Snowmass, ...



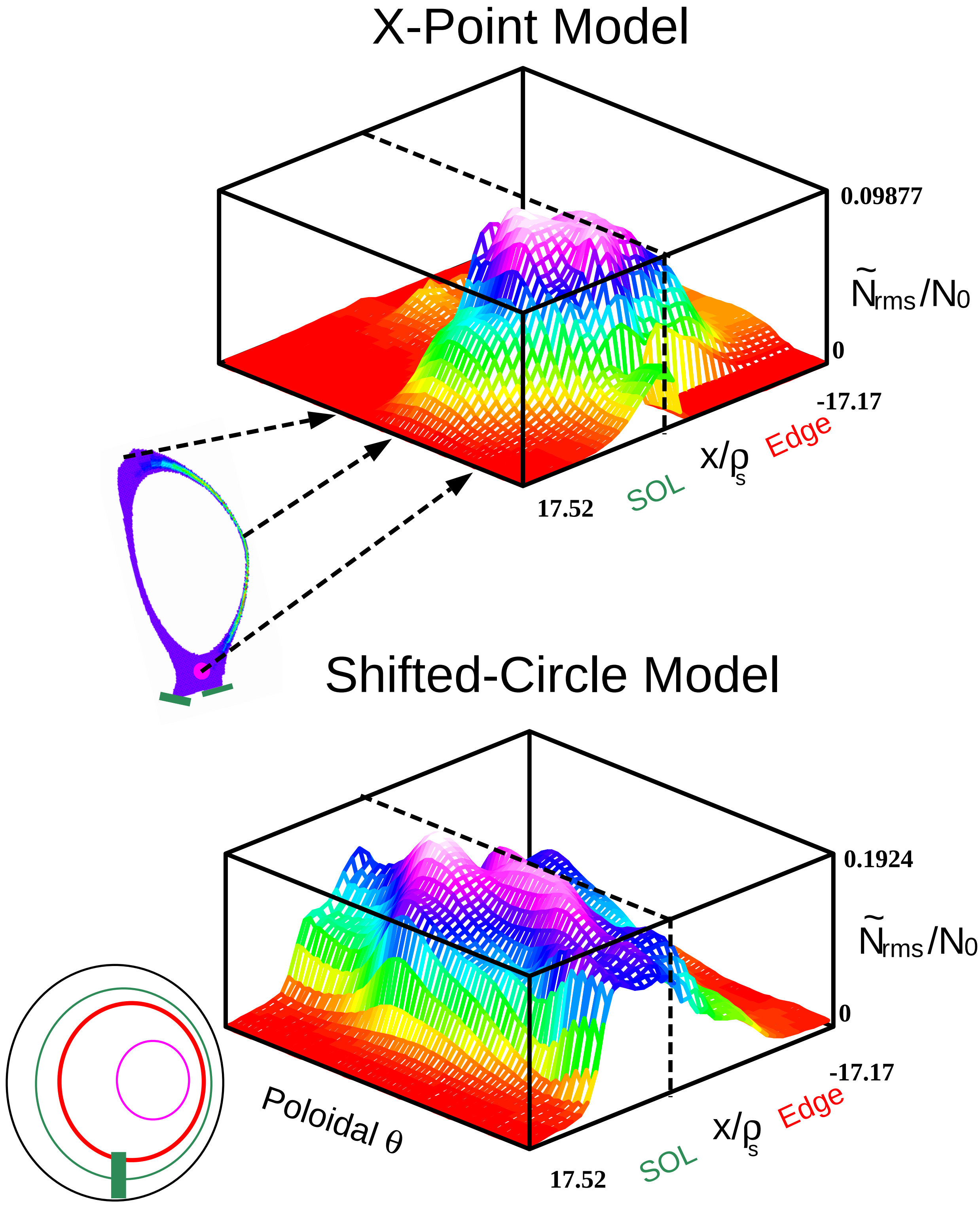
Local Safety Factor, $\nu(\psi,\theta)$, has strong variations near X-points that affect mode

$$\nu(\psi,\theta)=a_{eff}\,Bt/(RBp)$$

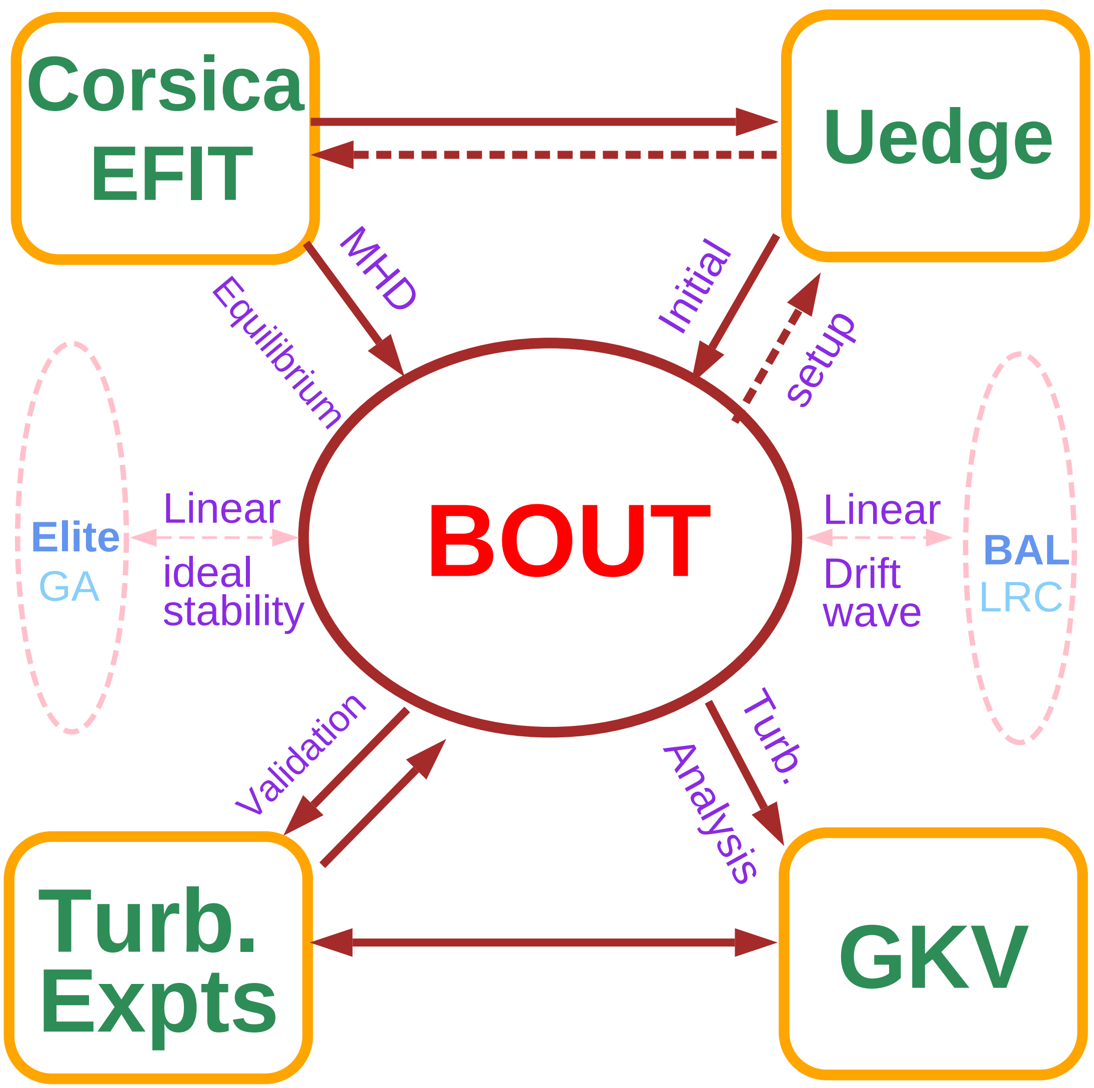


- ☞ Strong X-point shear
- ☞ long connection length

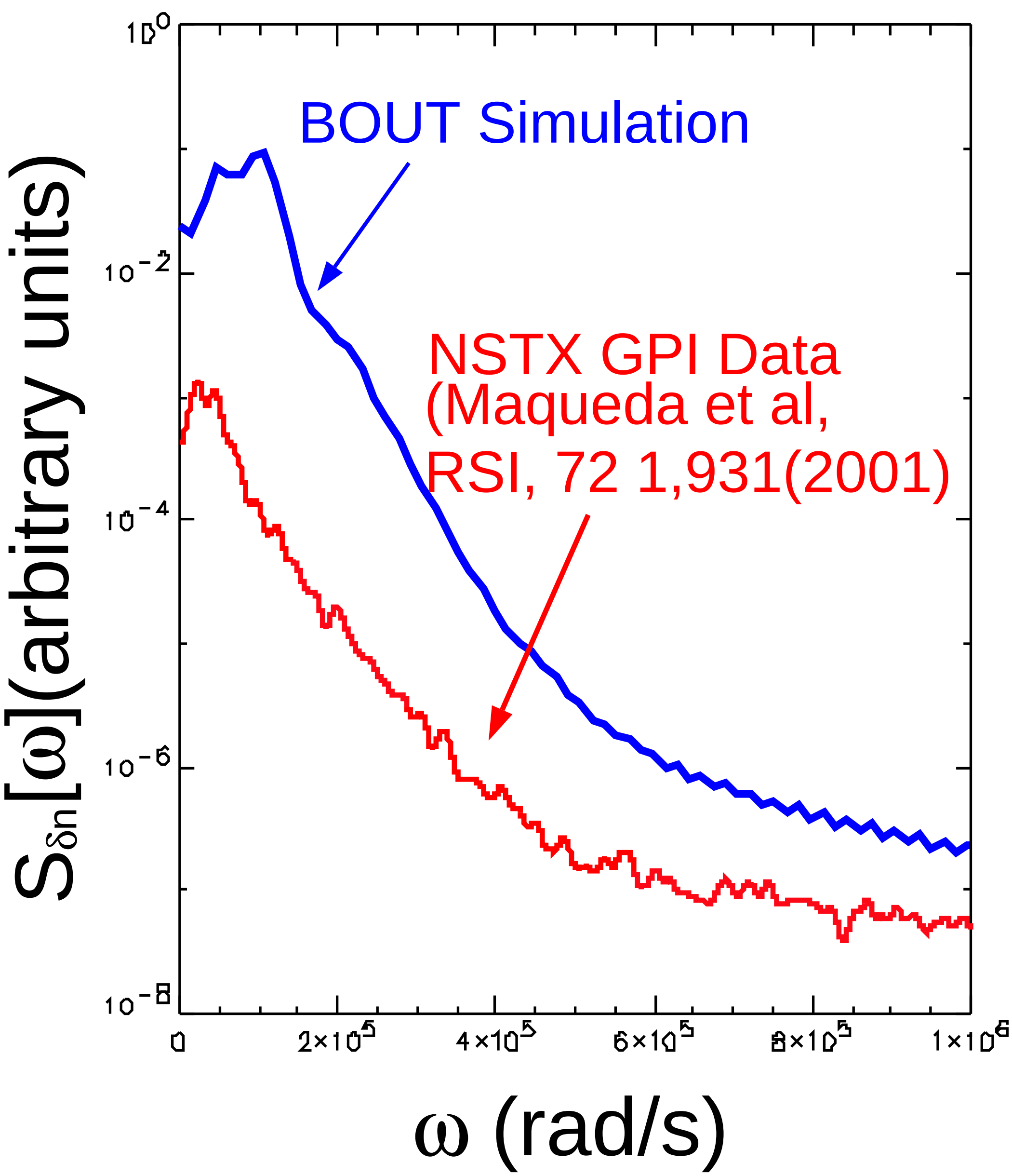
Density fluctuation is ballooning for X-point geom. vs. flute for shifted-circle



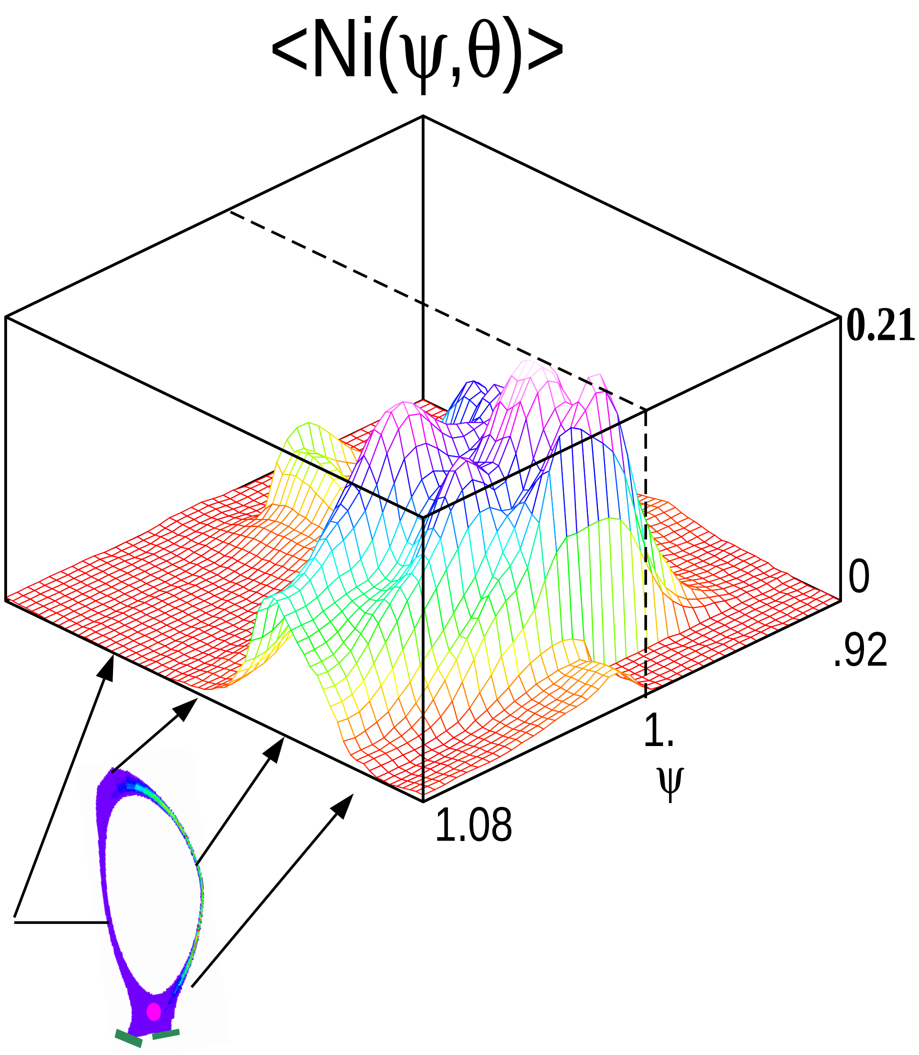
A suite of the codes work together to make BOUT simulation results similar to real experiments

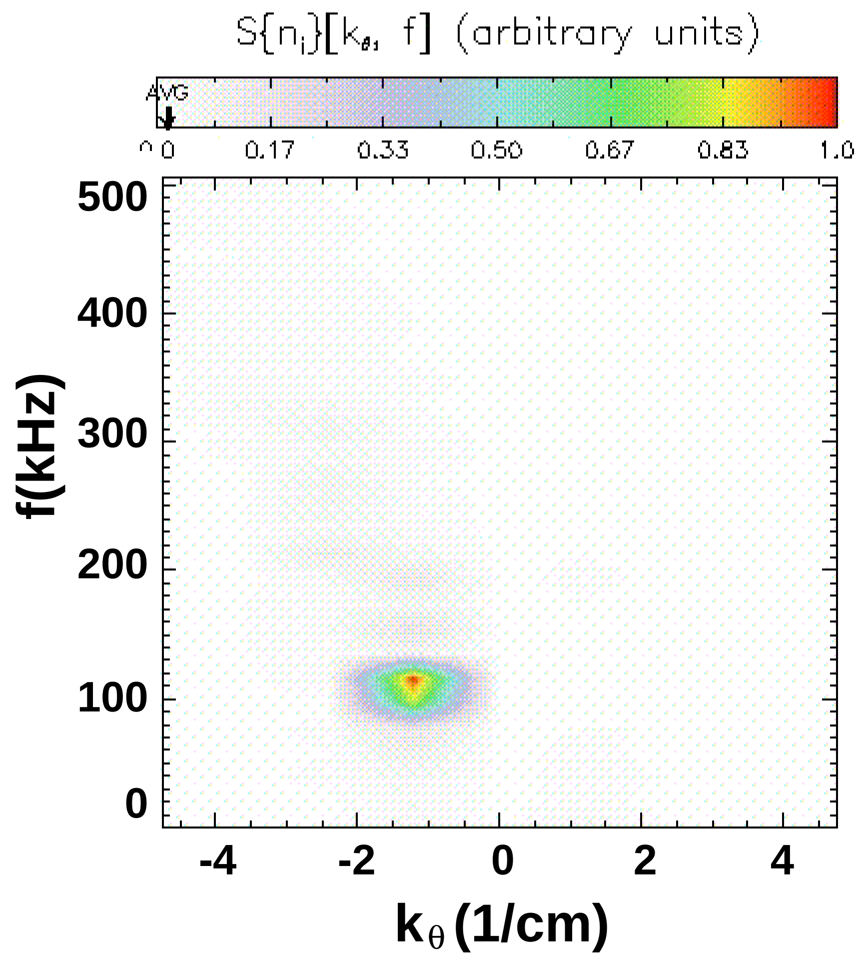


BOUT shows similar frequency spectrum as Gas Puff Image



BOUT Simulates Mode Similar to C-Mod Quasi-Coherent Mode





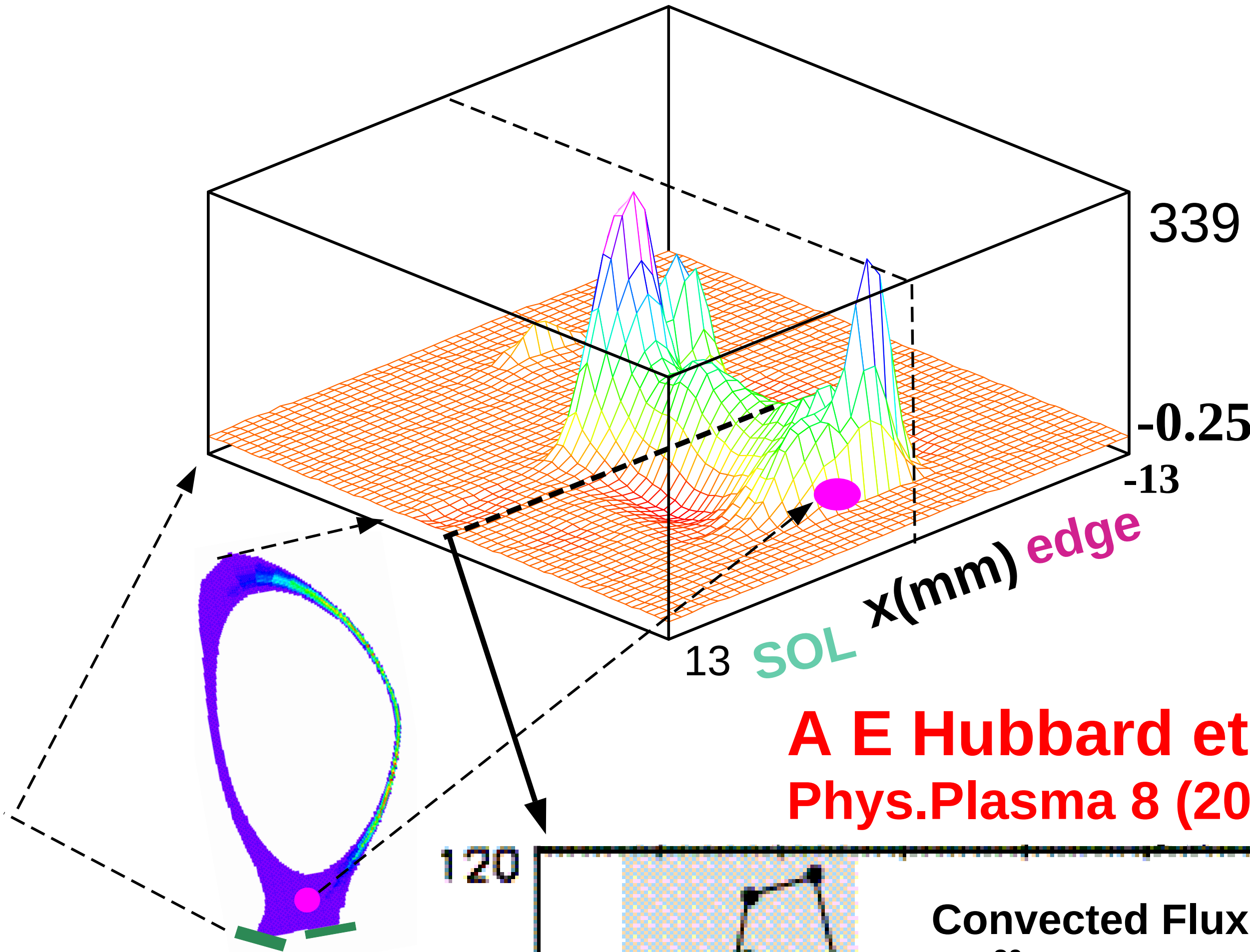
- Strong Dissipation near X-point

  → Resistive X-point Mode

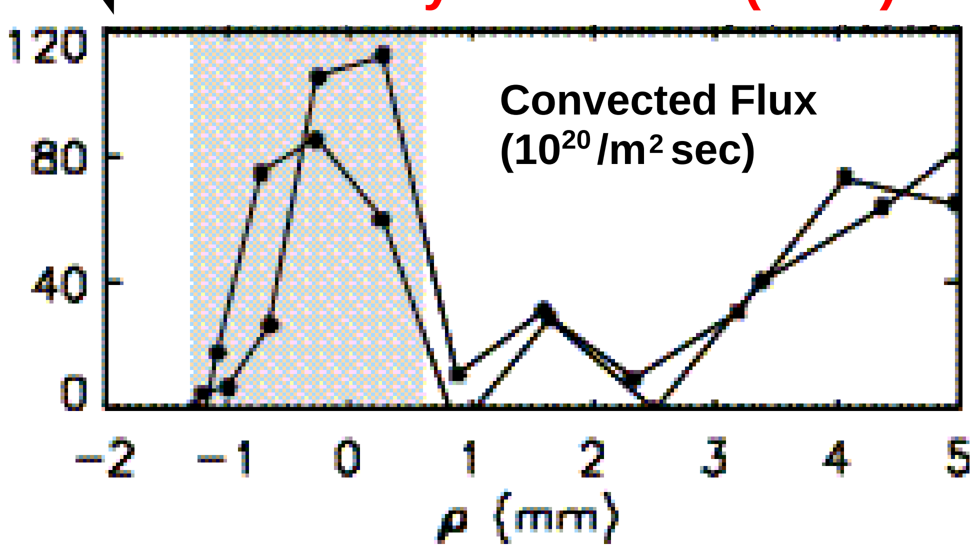
- Code Result well Localized in f and k_θ resembles PCI measurements

Particle Flux Γ_ψ is consistent with probe measurement near midplane region

$\Gamma_\psi = <\delta n \delta v_\psi>$ ($x10^{20}$ /m^2 s)

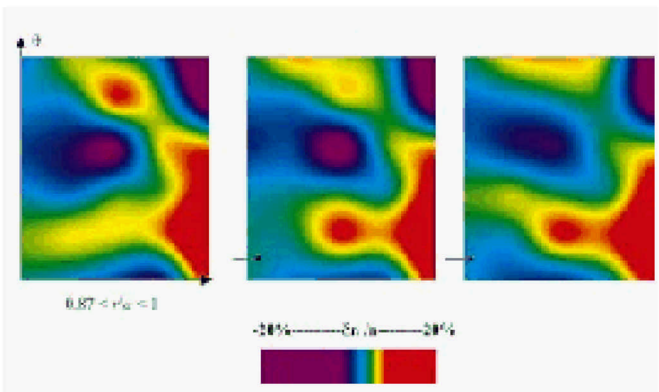


A E Hubbard et al
Phys.Plasma 8 (2001)

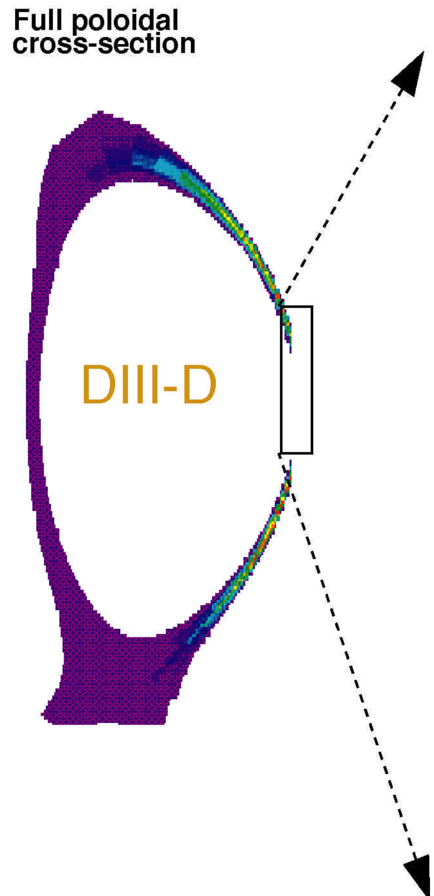


L-Mode Edge Turbulence in DIII-D

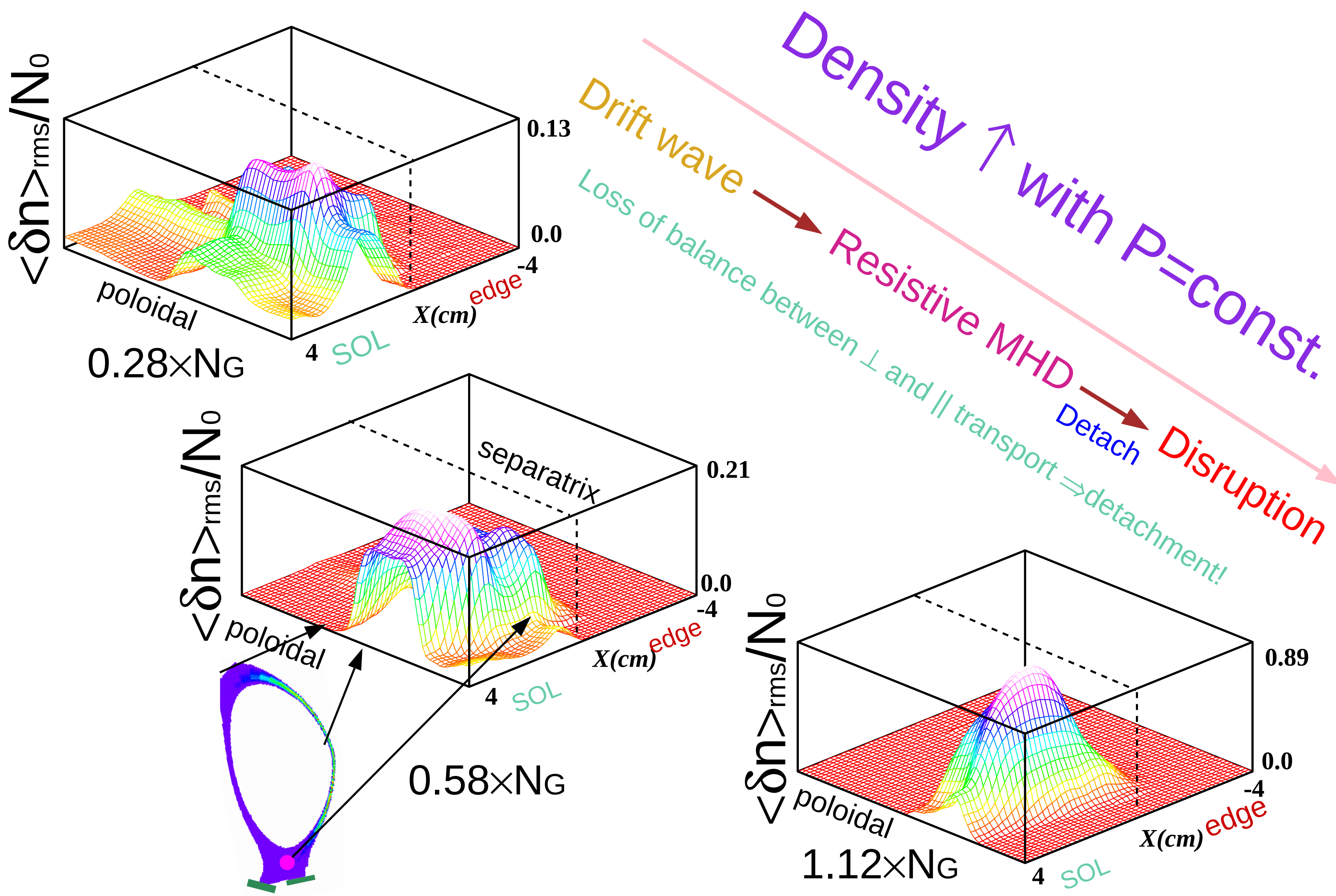
BES Expt.



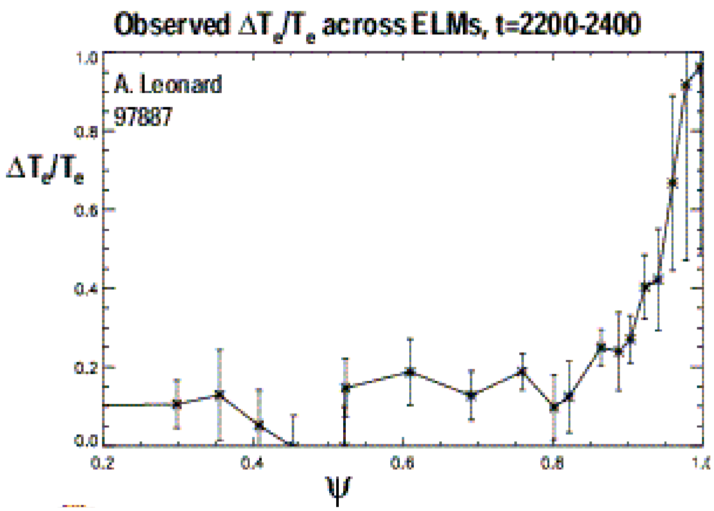
Time

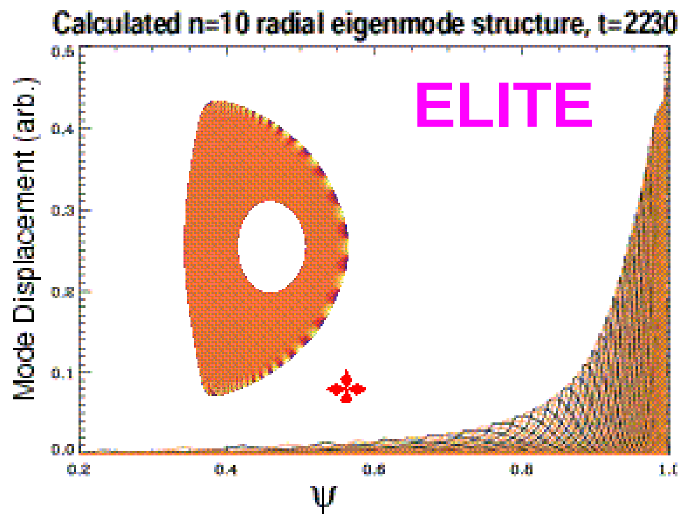


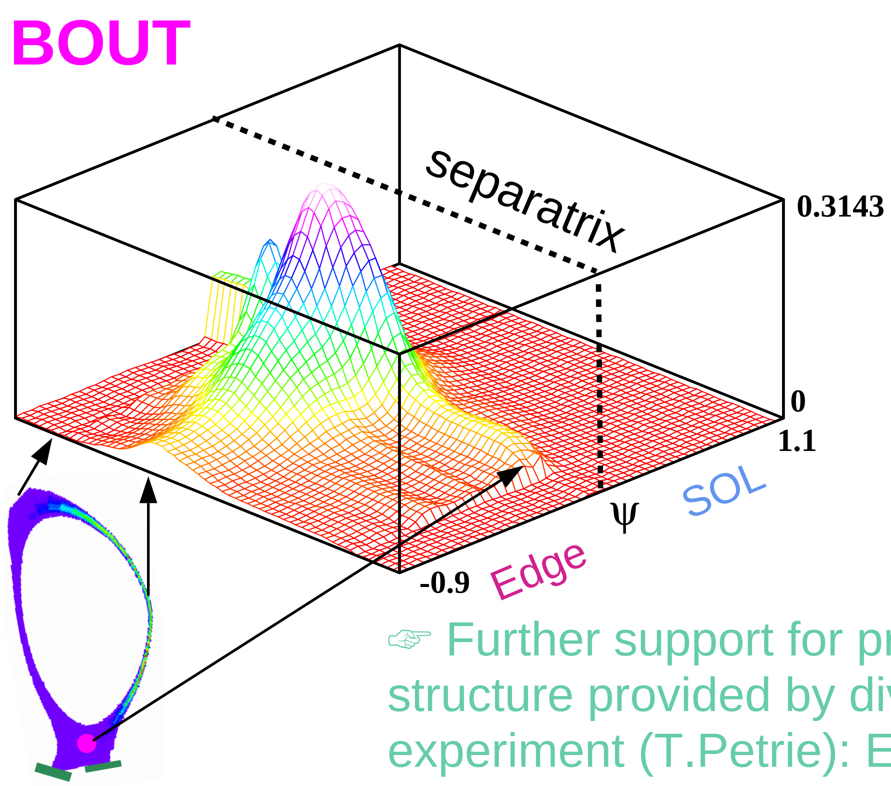
Dansity Limit: High collisionality ⇒ fluctuation level/transport ↑ and parallel correlation length ↓



Calculated Mode Structure from BOUT and ELITE Consistent with Observed DIII-D ELM Depth



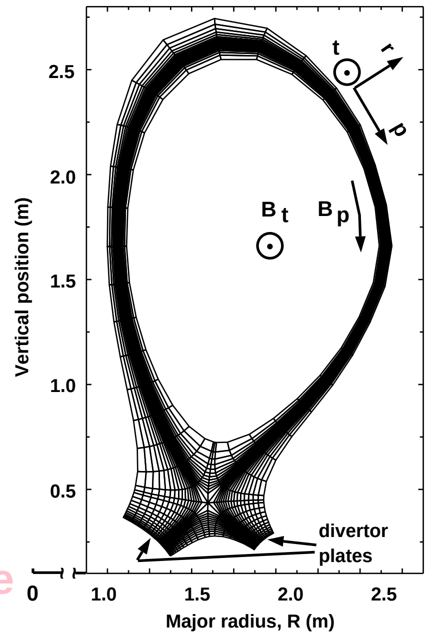


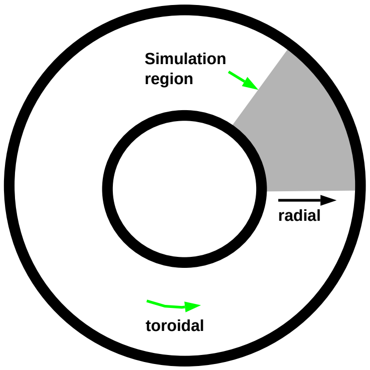


☞ Further support for predicted mode structure provided by divertor balance experiment (T.Petrie): ELM signals absent on high field side for double-null

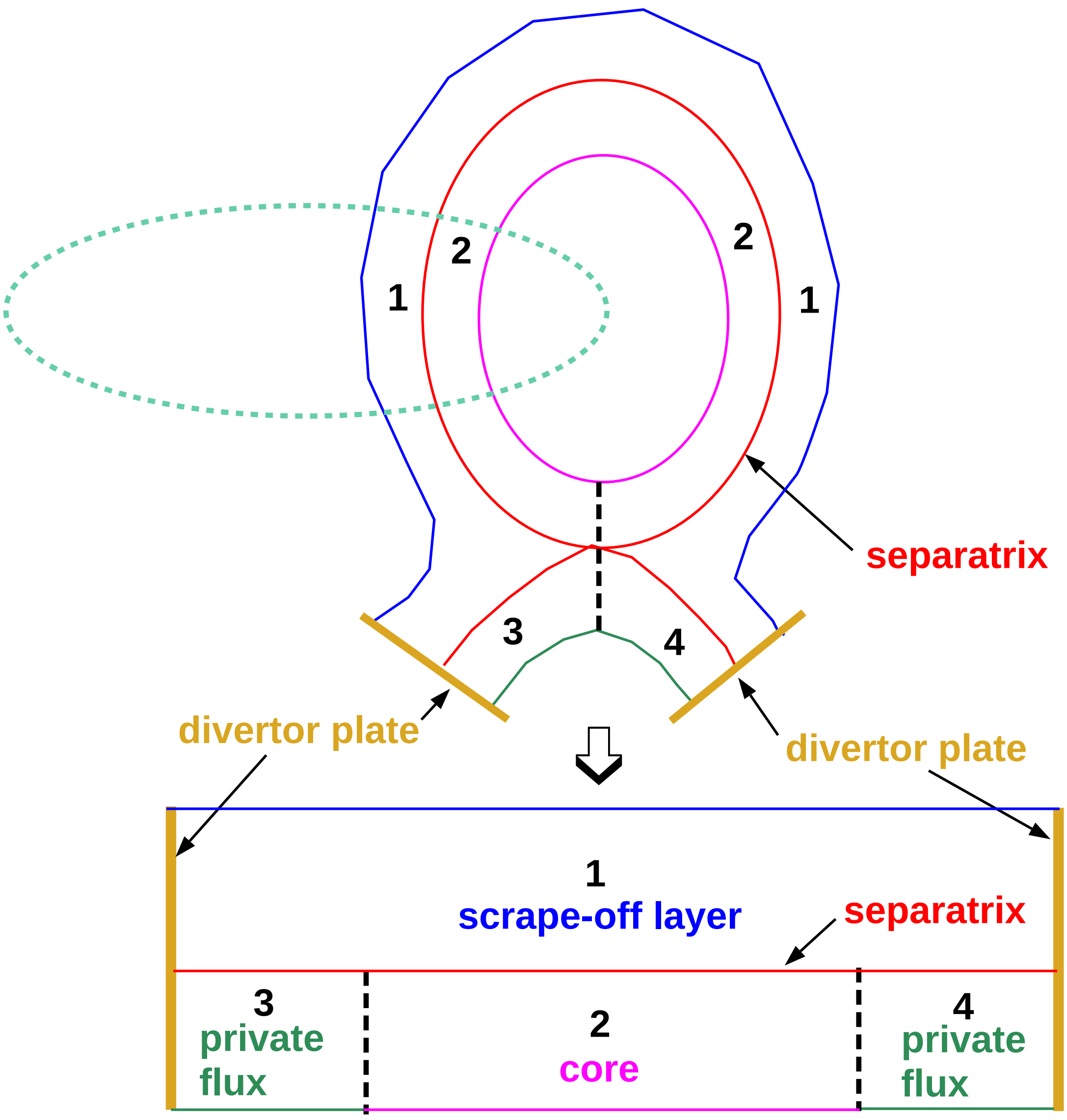
BOUT is a parallelized 3D nonlocal electro-magnetic turbulence code using MPI

- The BOUT code solves for the plasma fluid equations in a 3-D toroidal segment.
- BOUT uses a fully implicit Newton-Krylov solver PVODE.
- BOUT is a parallelized code based on domain decomposition that uses the MPI system.
- BOUT has been tested on Linux PC clusters, Sun and DEC workstation clusters, and on the NERSC IBM SP and Cray-T3E.
- Parallel for one direction; parallelization in second direction is under way, will use~1000---10000 PEs
- Mflop/s rates achieved is typically ~ 5---10% on IBM SP

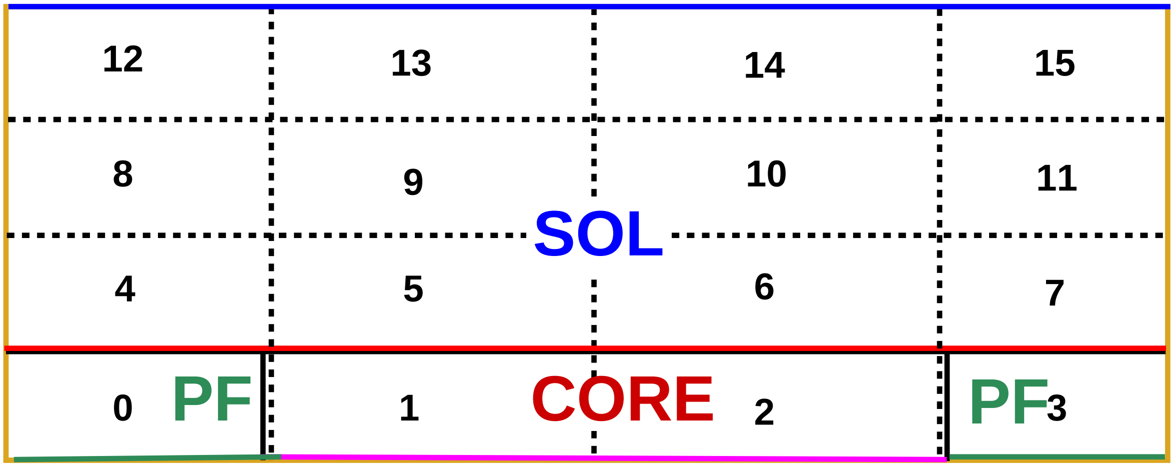


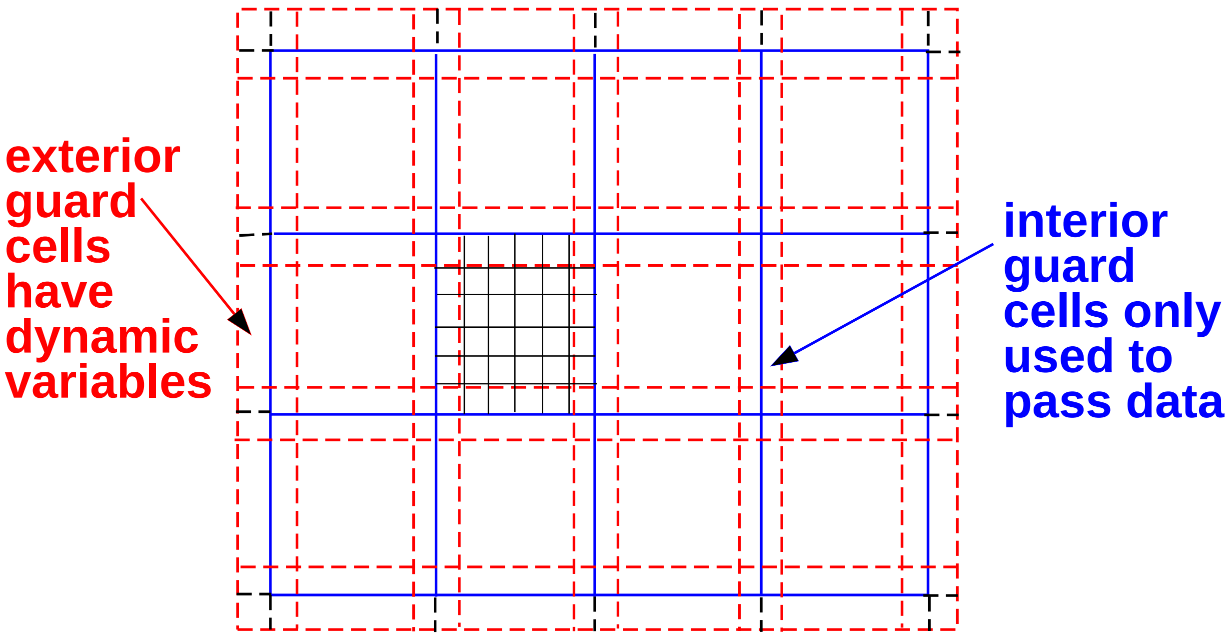


The poloidal plane is divided into four main regions for the domain decomposition model

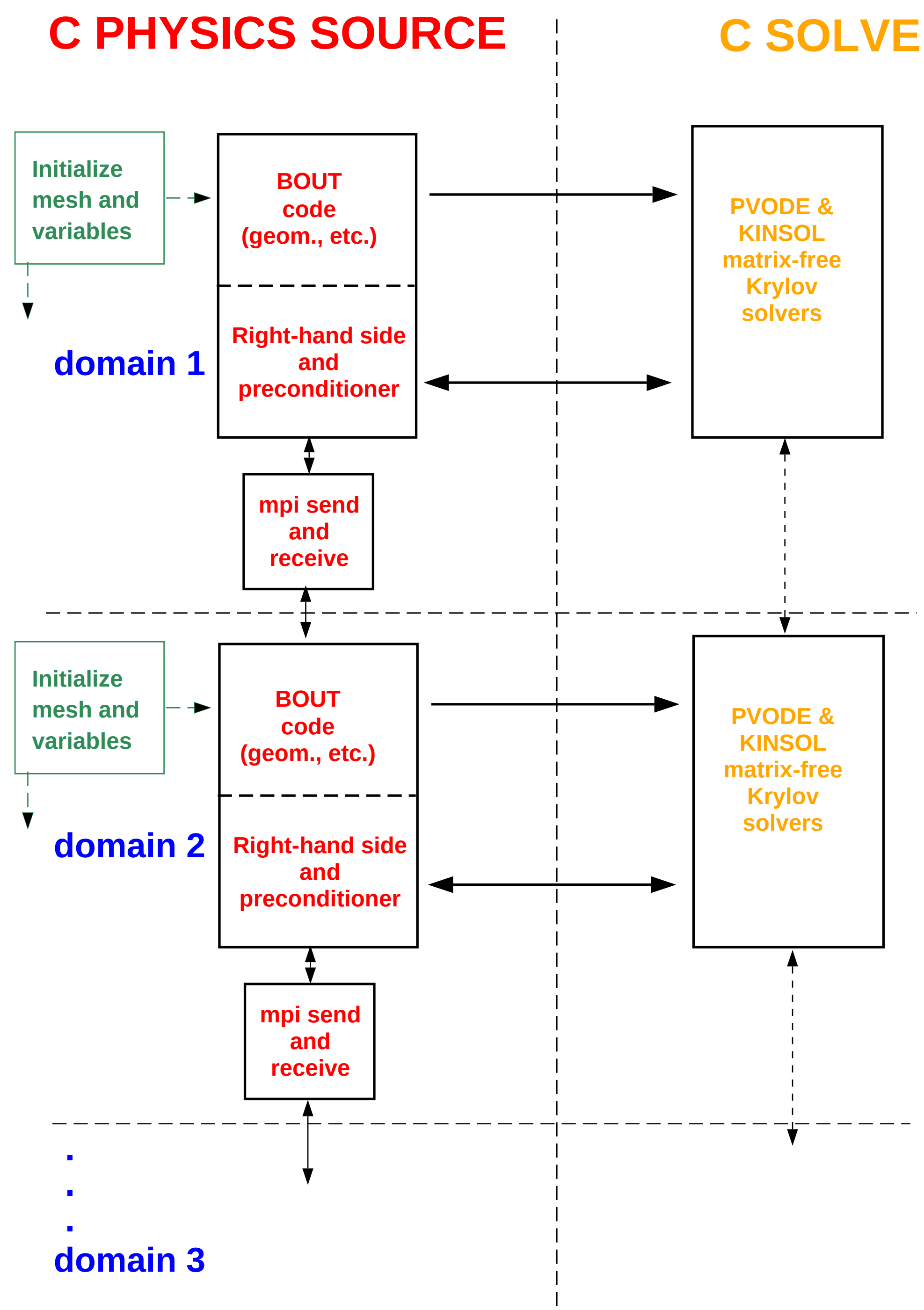


Each of four main regions can be futher subdivided for the domain decomposition model

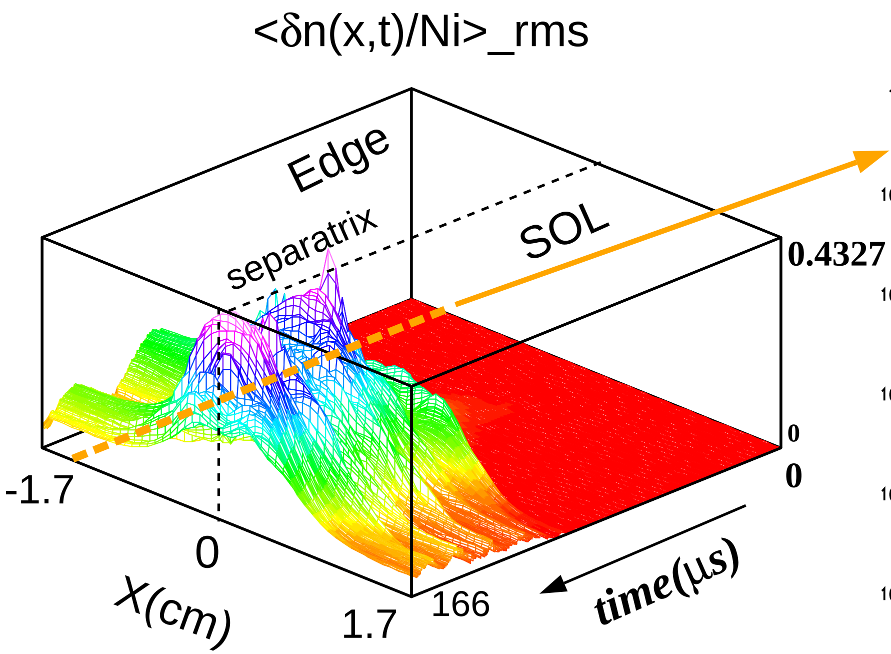


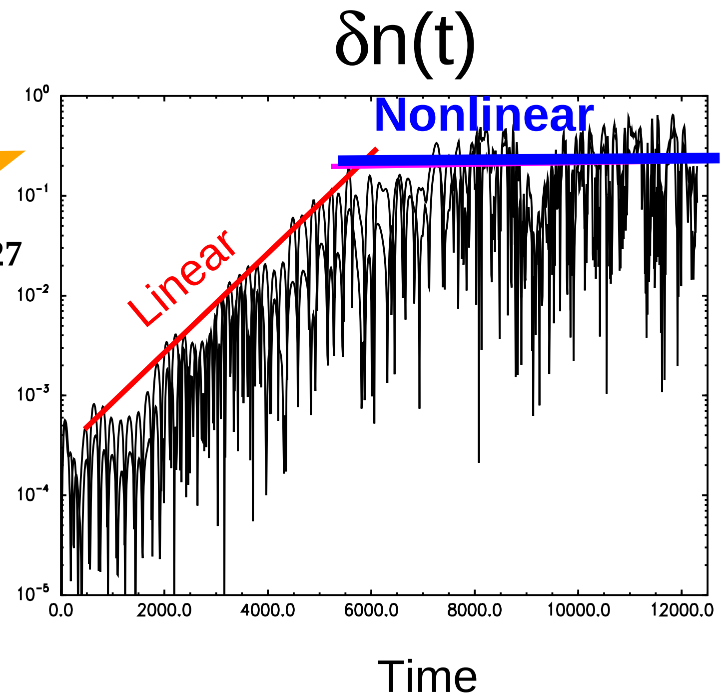


Schemic showing the two major components of parallel BOUT Code as replicated on each domain processor

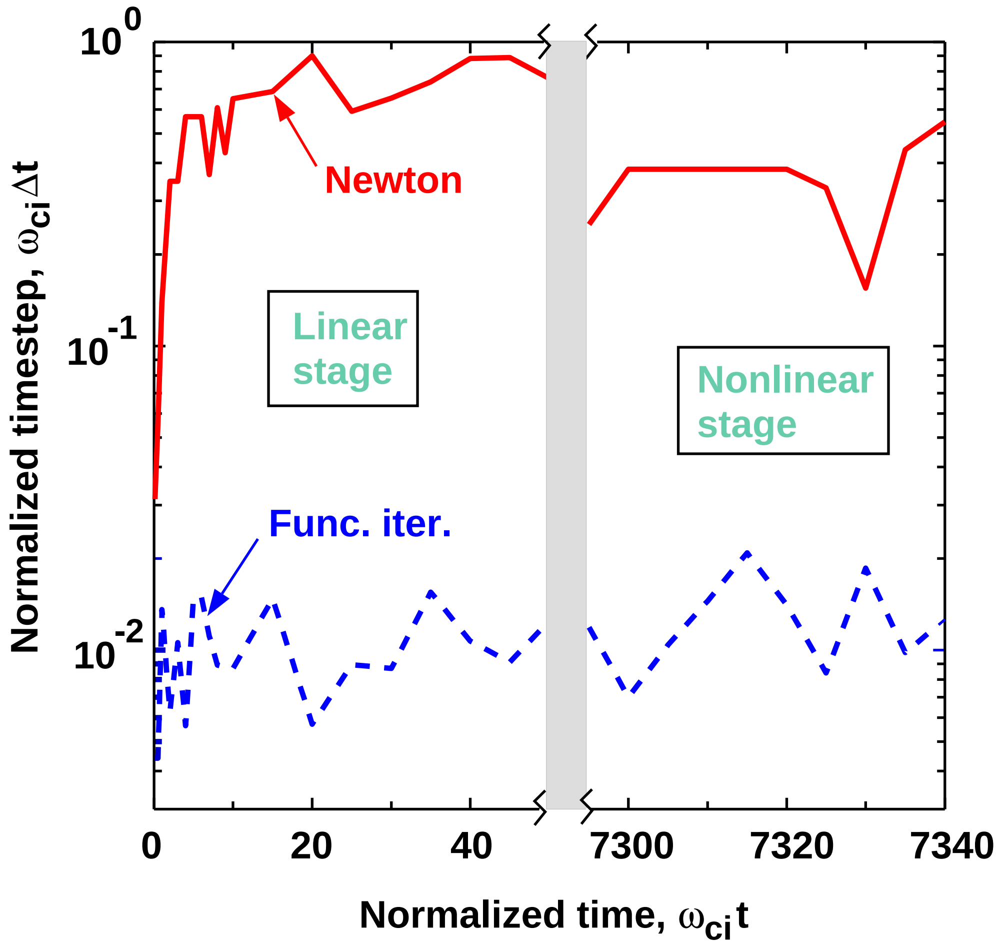


Time history of linear growth and turbulence saturation





Time step showed in BOUT over the course of a time-dependent simulation showing improvement with Krylov vs. func. iter.

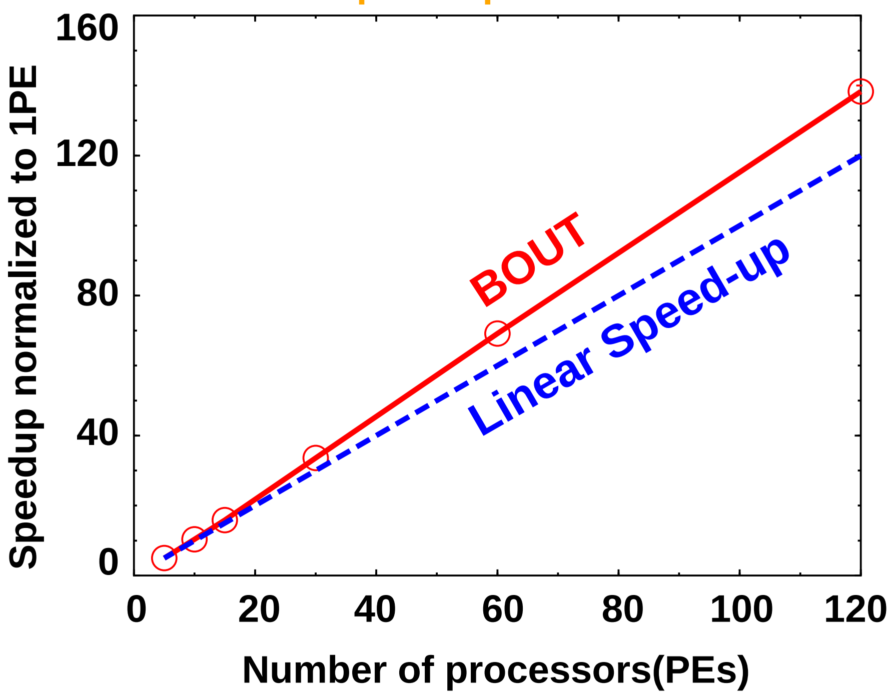


Comparison of Adams Predictor-Corrector and Newton-Krylov (BDF) Statistics in Linear Stage of the Simulation

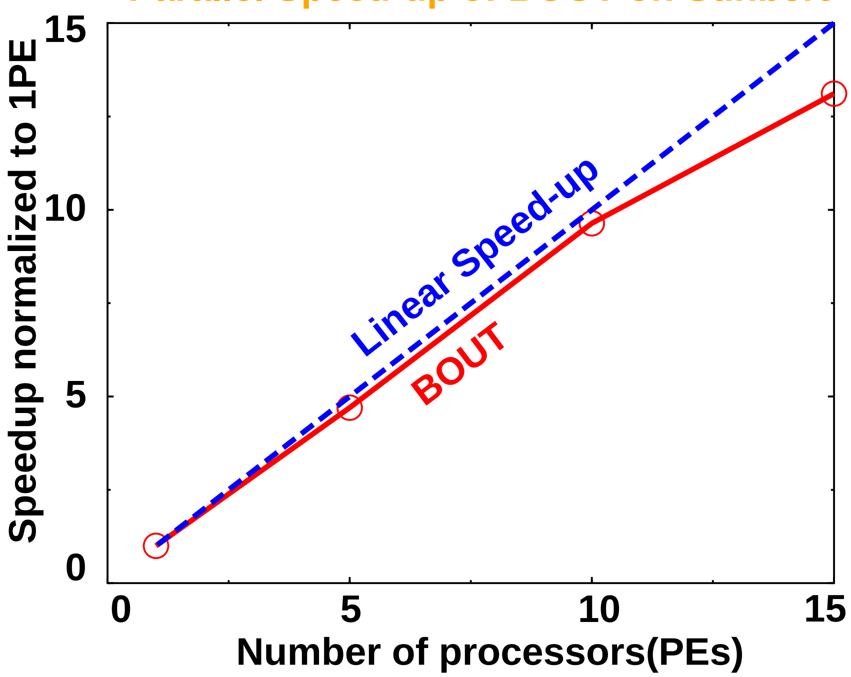
Method	Number of RHS evaluations	Number of time steps	Average $\Omega_{ci}\Delta t$	Observed Δtorder
One-step P/C	6212	5756	0.01	1
BDF Newton	1091	115	0.7	3-4

BOUT results show an almost linear speedup on T3E and Sunbert

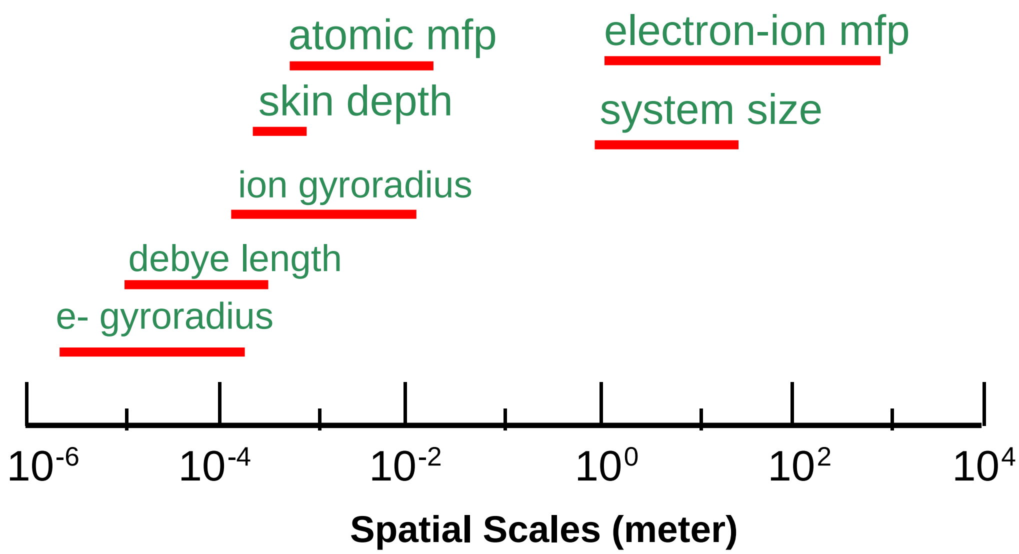
Parallel Speed-up of BOUT on T3E

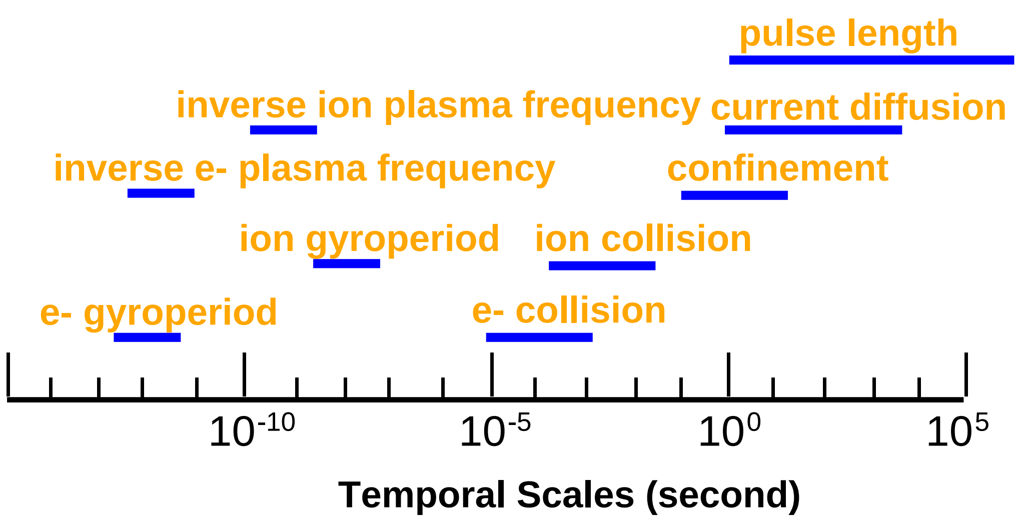


Parallel Speed-up of BOUT on Sunbert



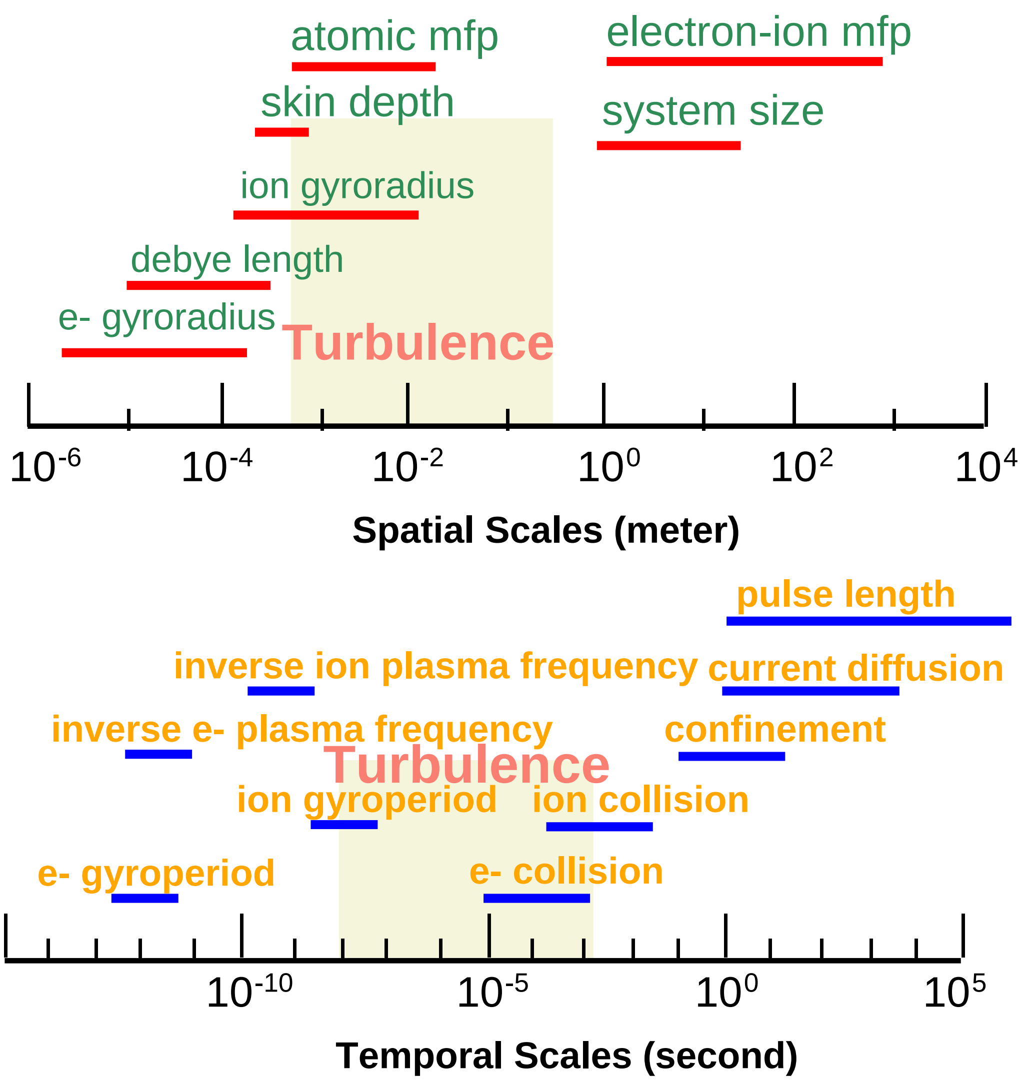
Huge range of spatial and temporal scales is a challenge to theory and simulations





☞ Overlap in scales often means that strong theoretical ordering is not possible

BOUT simulates only part of boundary problems---Turbulence



☞ It is even not possible to simulate whole boundary physics yet on today machines

BlueGene/L will provide enough computing power to simulate boundary physics

A proposed Kinetic BOUT code: 2V3D

- Resolution $30\times30\times100\times100\times1000\sim10^{10}$,
  $\Delta x\sim$ 1mm, ion gyroradius spatial scale,
  $\Delta t\sim10^{-8}$ second, Alfven time scale

- Time ~ 10 --- 100 ms,
  Thus number of timestep ~ 1×10^{6} --- 1×10^{7}

- Number of operation/grid point/step ~ 1000

- Total operations count to carry out the simulations ~10^{19}---10^{20}

- With a 100 TF machine, the time required

  $\sim10^{19}$ ---10^{20} /($10^{14}\times3600$)~30 --- 300 hours

Issues of BOUT performance on BlueGene/L

- The division of work for BOUT on IBM SP ~ 100 PEs:
  - 80% for evaluating the BOUT physics equations,
  - 1% for I/O,
    - a pointer variable is set so that each processor only reads a subset of the data needed for its domain.
    - each processor writes and reads its own dump file for the data in its domain for restarting the problem.
  - 12% for internal PVODE calculations,
  - 6% for interprocessor MPI communications,
  - 1% for other overhead costs,
  - 1% variation for the load balance among processors.

- We anticipate use ~10000 PEs on BlueGene/L,
  - ~ a flux tube per PE
  - Issues:

    Parallel I/O:

    Communications: Latence & bandwidth

    File management:~1000-10000 files per simulation

    Storage: ~ 1TB of data per simulation

    Unknown: